

The acceleration of heavy ions in the Stockholm 225-cm cyclotron

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With 22 figures in the text

ABSTRACT

A description is given of the acceleration and bombarding techniques used in the work on heavy ions with the 225-cm cyclotron at the Nobel Institute of Physics, Stockholm. With the present oscillator frequency this machine can accelerate heavy ions with mass-to-charge ratios up to about 3.7. The nominal energy at a radius of 90 cm (exit radius) is about 11 MeV/nucleon.

Some results of an investigation of the energy distribution of $^{12}\text{C}^{4+}$ beams are reported. It is shown that this distribution contains, together with the high-energy peak of $^{12}\text{C}^{4+}$ ions, a low-energy component. At a radius of 80 cm, where the mean energy for the $^{12}\text{C}^{4+}$ peak is roughly 100 MeV, the low-energy component has a distribution maximum below 30 MeV.

1. Introduction

In the past few years accelerated heavy ions (which in this connection means ions of atomic number greater than 2) have been of rapidly growing importance to nuclear physics [1].

Until about two years ago heavy-ion acceleration was performed exclusively in cyclotrons, disregarding a few early attempts to accelerate very heavy ions in experimental linear accelerators [2].

The first cyclotron-produced heavy-ion beam was obtained in 1940 by Alvarez [3] who accelerated six-charged carbon ions in the 37-inch Berkeley cyclotron. The work at Berkeley on heavy-ion acceleration was continued by others with the Crocker 60-inch cyclotron. In this machine six-charged carbon and nitrogen ions [4] as well as six-charged oxygen ions [5] have been accelerated.

Several years ago a 63-inch cyclotron was designed and built at the Oak Ridge National Laboratory, U.S.A., for the production of triply-charged nitrogen ions of relatively low energies (less than 30 MeV) [6].

From an early stage, the 60-inch cyclotron at the University of Birmingham has been used for acceleration of six-charged carbon, nitrogen and oxygen ions [7, 8]. Beams of six-charged nitrogen and oxygen ions have been produced also in the cyclotron at Centre d'Études Nucléaires de Saclay [9].

In the 150-cm cyclotron at the Atomic Energy Institute of the Academy of Sciences of U.S.S.R. in Moscow, ions of carbon, nitrogen and oxygen in various charge-states

are produced [10]. The cyclotron at the Leningrad Physical-Technical Institute produces triply-charged nitrogen ions with energies less than 30 MeV [10].

For the past two years a linear accelerator (HILAC) at the University of California, Berkeley, is producing carbon, nitrogen, oxygen and neon ions with energies of 10 MeV/nucleon [11]. A similar machine built at the Yale University is also in operation [11].

In the beginning of 1953 work on heavy-ion acceleration was started with the 225-cm cyclotron at the Nobel Institute of Physics. During the first years six-charged ions of carbon, nitrogen and oxygen were accelerated. A preliminary report on this work was published several years ago [12]. Since then the beam intensities have been increased. In the spring of 1955 the oscillator frequency was changed in order to make possible acceleration of ions with mass-to-charge ratios up to about 3.7. Since this time the machine has been able to produce, not only the above-mentioned ions, but also six-charged ions of both ^{20}Ne and ^{22}Ne . It has also been possible to accelerate ^{12}C and ^{13}C ions in the four-charged state.

The purpose of the present paper is to give a description of the techniques used in the work on heavy-ion acceleration in the 225-cm cyclotron. Some results of an investigation of the energy distribution for $^{12}\text{C}^{4+}$ ions are also reported.

2. Production of heavy ions

2.1. General

The most difficult problem which has to be approached if a 60-inch cyclotron is to be used for acceleration of, for instance, nitrogen and oxygen ions to high energies (100 MeV or more) is the production of ions with high charges. For a given frequency of the accelerating voltage, the choice of charge state for the ion to be accelerated depends on the maximum attainable magnetic induction. This is seen from the following relation, which gives the magnetic induction for resonance under non-relativistic conditions:

$$B = 2\pi f(m_0/q) \quad (1)$$

Here B is the magnetic induction, m_0 the rest mass of the ion, q the charge and f the oscillator frequency. Expression (1) shows that a lower frequency makes possible the acceleration of ions with higher m_0/q values. However, if the acceleration is performed at a lower frequency, the energy at a given radius will also be lower and this can be compensated for only by increasing the orbit radius.

In the Stockholm 225-cm cyclotron [13] an energy of about 11 MeV/nucleon can be attained at a radius of 90 cm by the use of a relatively low oscillator frequency (8.1 Mc/sec). At this frequency, the maximum magnetic induction (which is about 20 kilogauss) makes possible the acceleration of ions with m_0/q values up to about 3.7 (expressing m_0 in atomic mass units and q in units of the electronic charge). This is illustrated by Fig. 1 in which the central magnetic induction is plotted as a function of the magnet current. The induction values for the acceleration of a variety of ions are indicated. As shown in this figure, all heavy ions except those of ^{12}C and ^{13}C have been accelerated in the six-charged state.

When the work on heavy ion acceleration was started in the Stockholm cyclotron (1953), no cyclotron ion source could produce useful intensities of six-charged heavy ions. In the Stockholm machine, therefore, the same method as used in the 60-inch

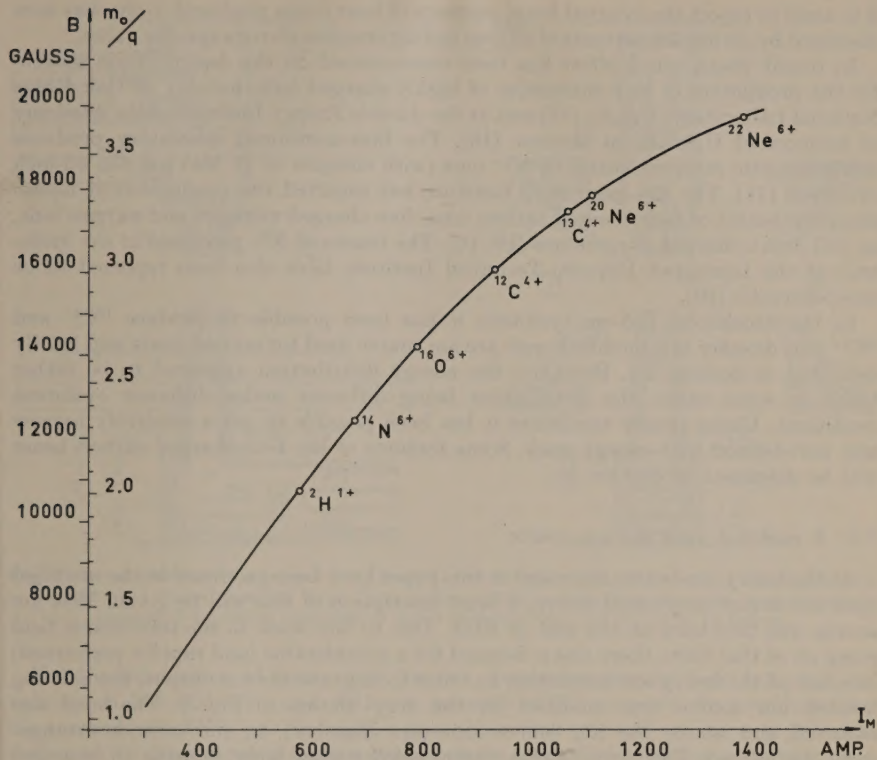


Fig. 1. The central magnetic induction B plotted as a function of the magnet current I_M for the Stockholm 225-cm cyclotron. The circles represent the various ions accelerated. A scale for m_0/q is also given (m_0 is the rest mass of the ion in mass units; q is the charge carried by the ion in units of the electronic charge).

cyclotrons at Berkeley and in Birmingham for producing six-charged heavy ions was utilized. This method is based on third-harmonic pre-acceleration of doubly-charged ions, part of which are stripped by collisions with gas atoms to the six-charged state¹. During the third-harmonic acceleration, the doubly-charged ions move at a revolution frequency which is one third of the cyclotron frequency. For a given radius the doubly-charged ions will attain an energy which is 1/9 of that of the six-charged ions.

A serious disadvantage connected with this method of producing the six-charged ions is that it leads to a continuous energy distribution, the maximum of which is far below the nominal energy corresponding to the radius used. Due to this fact,

¹ This two-step process was discussed by Hollander in an unpublished report on acceleration of six-charged carbon ions [14]. Independent work performed with the Birmingham 60-inch cyclotron by Walker and Fremlin [7] and Walker *et al.* [8] demonstrated clearly the importance of harmonic pre-acceleration for the subsequent stripping of electrons.

it is usual to report the internal beam currents of heavy ions produced in the way now discussed by giving the currents of all ions having energies above a specific value.

In recent years, much effort has been concentrated on the design of ion sources for the production of high intensities of highly-charged ions, notably at Oak Ridge National Laboratory, U.S.A., [15] and at the Atomic Energy Institute of the Academy of Sciences of U.S.S.R. in Moscow [16]. The first-mentioned laboratory produces monoenergetic external beams of N^{3+} ions (with energies of 27 MeV) in the 63-inch cyclotron [11]. The last-mentioned institute has reported the production of monoenergetic beams of four-charged carbon ions, five-charged nitrogen and oxygen ions, as well as six-charged oxygen ions [10, 16]. The beams of N^{3+} produced in the cyclotron at the Leningrad Physical-Technical Institute have also been reported to be monoenergetic [10].

In the Stockholm 225-cm cyclotron it has been possible to produce $^{12}C^{4+}$ and $^{13}C^{4+}$ ions directly in a modified open arc ion source used for several years and briefly described in Section 2.2. However, the energy distribution appeared to be rather broad in some cases, the distribution being different under different cyclotron conditions. Under proper conditions it has been possible to get a relatively narrow and well-defined high-energy peak. Some features of the four-charged carbon beam will be discussed in Section 5.

2.2. *A modified open arc ion source*

As the heavy-ion beams discussed in this paper have been produced in the modified open arc source mentioned above, a brief description of this will be given. This ion source was first tried at the end of 1953. Due to the work in the transuranic field going on at that time, there was a demand for a considerable (and rapidly performed) increase of the heavy ion intensities. In order to improve the ion output, the existing hooded ion source was modified in the way shown in Fig. 2. The hood was removed and above the ion source cone (arc chamber), an anti-cathode arrangement was placed. This consists of a water-cooled copper body, housing an insulated electrode (in the arrangement finally made, a piece of tantalum was used). This electrode can be connected to a negative voltage or kept floating. Thus, the electrode acts as a reflector for the primary electrons (cf. ref. 6). Gas is introduced into the ion source cone through a hole above the filament (see Fig. 2). The ion source filament (a U-shaped wolfram wire, 2.5 mm in diameter) is heated with direct current supplied by a selenium rectifier. Power for the arc is supplied by a dc generator (giving maximum 1 kV and 5 amperes).

Provisions are made for introducing gas through the anti-cathode housing. In some experiments with $^{12}C^{4+}$ ions, carbon dioxide was introduced both through the anode cone and the anti-cathode housing. These experiments indicated that the maximum beam current was always obtained for a specific value of the total gas pressure (about 1×10^{-5} mm Hg).

The effect of the floating anti-cathode has been investigated in some experiments using $^{12}C^{4+}$ ions. For this purpose the anti-cathode was, in some runs, connected to ground and, in other runs, left floating. Comparisons between the carbon beams in the two cases were made for various arc voltages (maximum 300 volts) and various arc currents (maximum 2.5 amperes). By using the anti-cathode as a reflector, an increase of the beam current by a factor of between 2 and 3 could be attained (the increase being dependent on the arc conditions used).

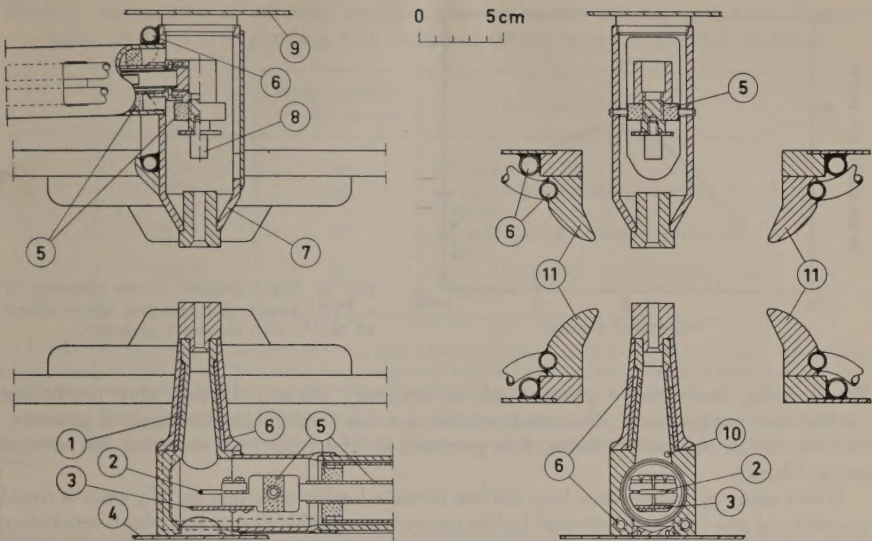


Fig. 2. The modified arc ion source. 1 ion source cone (arc chamber). 2 filament. 3 shield (wolfram or tantalum). 4 lower chamber liner. 5 insulation (Teflon). 6 cooling channels. 7 anti-cathode housing. 8 tantalum electrode. 9 upper chamber liner. 10 gas inlet. 11 feelers.

For the production of heavy ions, the ion source has usually been run with arc voltages of 200–400 volts and with arc currents of 2–3 amperes. In particular, for the acceleration of C^{4+} ions the highest possible arc voltages and arc currents (350–400 volts and 2.5–3 amperes, respectively) have been used. Due to arcing at the filament holders occurring at voltages of about 350–400 volts, it has not been possible to exceed this voltage range.

The heavy-ion beam currents produced by this ion source are specified in Section 2.4.

In addition, it may be mentioned that the 225-cm cyclotron, which at time of writing is being reassembled after remodeling, will now be provided with an arc ion source of the slit-type (in principle of the hot-cathode type used in the Oak Ridge 63-inch cyclotron [15]). In this connection it may be noted that, according to Fig. 1, the acceleration of $^{14}N^{4+}$ and $^{16}O^{5+}$ will be possible at the present oscillator frequency.

2.3. Gas supply

As the beam current is very sensitive to the gas flow through the ion source, maximum beams cannot be attained without having the possibility to change the gas flow with the beam on, i.e. from the control desk. Also, of course, the gas flow must be kept constant during the run. The energy spectrum also depends on the gas pressure (cf. [8]).

To regulate the gas flow in the ion source described above, a motor-operated needle valve is used. The regulation of the gas stream is facilitated by the use of reduced pressure (usually 300–400 mm Hg) on the inlet side of the needle valve.

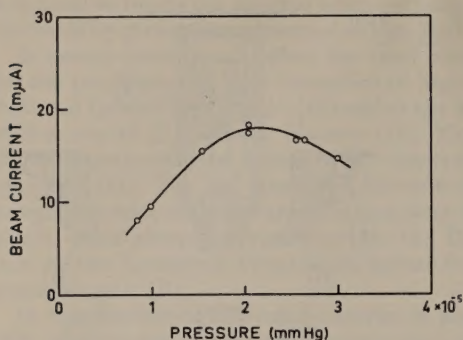


Fig. 3. The variation of the intensity of a $^{16}\text{O}^{6+}$ beam (for energies above about 95 MeV) with the tank pressure.

When using inexpensive gases, such as ordinary carbon dioxide (for producing carbon and oxygen ions), the gas is stored in a big tank under the desired pressure. Thanks to the big tank volume, this pressure is kept relatively constant for runs of several hours.

When using precious gases (e.g. carbon dioxide highly enriched in ^{13}C), only a small quantity of gas can be connected to the ion source. In this case a sufficient constancy of the inlet pressure is obtained in the following way. The gas container used for this purpose is a small rubber bladder (having a volume of about half a litre). This is housed in a big tank (with a volume of about 10 litres) containing air at a pressure of 300–400 mm Hg. With this simple arrangement the gas pressure is kept approximately constant until the rubber container is almost emptied.

In order to save gas when $^{13}\text{CO}_2$ is used, the machine is tuned by utilizing ^{13}C available in natural CO_2 . When the machine has been tuned, one can switch over from this gas to CO_2 enriched in ^{13}C . For this purpose, magnetically operated valves are used. In the same way the ^{22}Ne present in natural Ne gas is used when tuning the machine for the acceleration of ^{22}Ne ions.

In the acceleration of six-charged ions, produced by stripping of pre-accelerated doubly-charged ions, the stripping process has been improved by increasing the pressure in the acceleration chamber. For this purpose, a method consisting of introducing argon into the acceleration chamber, as used already in the early Birmingham experiments [8], has been adopted. In the Stockholm cyclotron the argon gas has been introduced into one of the dees via a tube inside the dee stem. The flow of this gas has also been remotely controlled.

In the acceleration of oxygen ions, carbon dioxide was sometimes used instead of argon. The stripping seemed to be improved to about the same degree by both gases.

The curve in Fig. 3 shows the variation of the $^{16}\text{O}^{6+}$ beam with tank pressure (measured by an ionization gauge connected to one of the dee stem tanks).

2.4. Beam intensities

Table 1 gives a summary of heavy-ion beam currents obtained in the 225-cm cyclotron. These currents are "meter" currents. They have been measured by means of either the standard probe or the foil probe (see Section 3). As only part of the

Table 1. Intensities of internal heavy-ion beams in the 225-cm cyclotron. The nominal energy corresponding to a radius of 90 cm is about 11 MeV/nucleon.

Ion	Probe position (radius in cm)	Internal beam current
$^{13}\text{C}^{4+}$	80	0.5–1 μA *
$^{14}\text{N}^{6+}$	85	up to 0.1 μA for energies above 100 MeV
$^{16}\text{O}^{6+}$	80	up to 0.1 μA for energies above 80 MeV
$^{20}\text{Ne}^{6+}$	80	up to 0.05 μA for energies above 120 MeV**

* The current was measured for energies above 85 MeV. The high-energy peak was in the range 90–110 MeV. For $^{13}\text{C}^{4+}$ ions the current of high-energy particles (at the same radius) was about half the beam strength of $^{13}\text{C}^{4+}$ ions when using CO_2 enriched to 60 % in ^{13}C .

** The intensities obtainable for $^{22}\text{Ne}^{6+}$ ions at the same radius (for energies above 130 MeV) is about 2/5 of the beam strength of $^{20}\text{Ne}^{6+}$ ions when using Ne gas enriched to almost 100 % in ^{22}Ne .

beam penetrates the measuring window of the probe, the measured value has in each case been corrected to give the total beam.

Carbon and oxygen ions have been produced from CO_2 or from N_2O and nitrogen ions from either N_2 or N_2O .

3. Bombarding and measuring techniques

3.1. Probe mechanism

For the utilization of the internal beams of heavy ions in the 225-cm cyclotron various probes have been designed. The outer part of such a probe (the probe stem) is made of a non-magnetic stainless-steel tube (maximum 70 mm in diameter). The probe can be inserted through an air lock into the dee gap. Outside the air lock the probe is attached to a four-wheeled trolley which can be moved along two tracks by means of a motor-driven chain. This arrangement is shown in Fig. 4. The trolley is seen in Fig. 5. To set the probe at the desired radius, the chain can be driven at a conveniently slow speed. To take the probe out, a fast withdrawal can bring the probe from its normal position between the dees to the air-lock in about 10 seconds. These axial movements can be controlled from the control room and the radius at which the probe head is set can be read on a meter at the control desk. As will be described below, some of the probe heads have two beam openings on opposite sides. To enable the use of either of these openings, the probe can be rotated through 180° by means of a pneumatic device also visible in Figs. 4 and 5. The back- and forth-movement of the pneumatically operated piston is transformed to a rotational movement by the use of a system of wires and pulleys. This rotational movement is also remotely controlled.

A view of the probe arrangement is shown in Fig. 6.

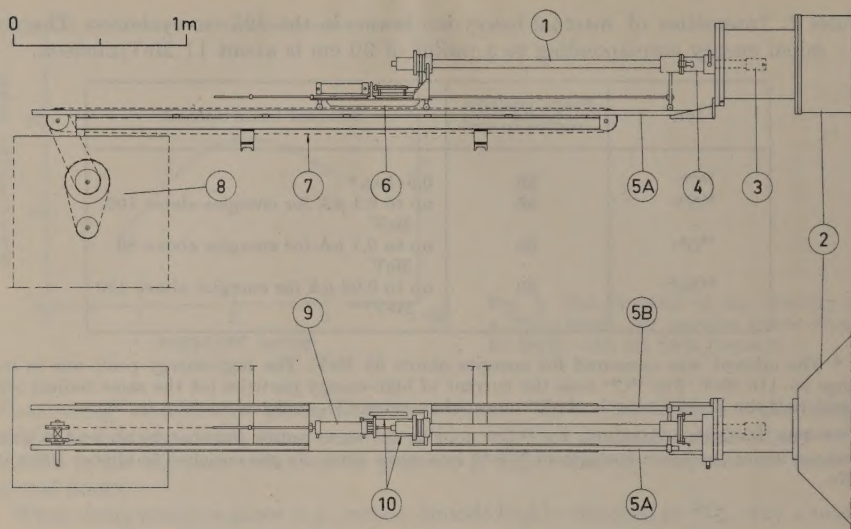


Fig. 4. Schematic drawing of the probe mechanism. 1 probe. 2 acceleration chamber. 3 probe head. 4 air lock. 5 A, 5 B tracks. 6 probe trolley. 7 chain. 8 motor housing. 9 pneumatic cylinder. 10 wires (cf. Fig. 5).

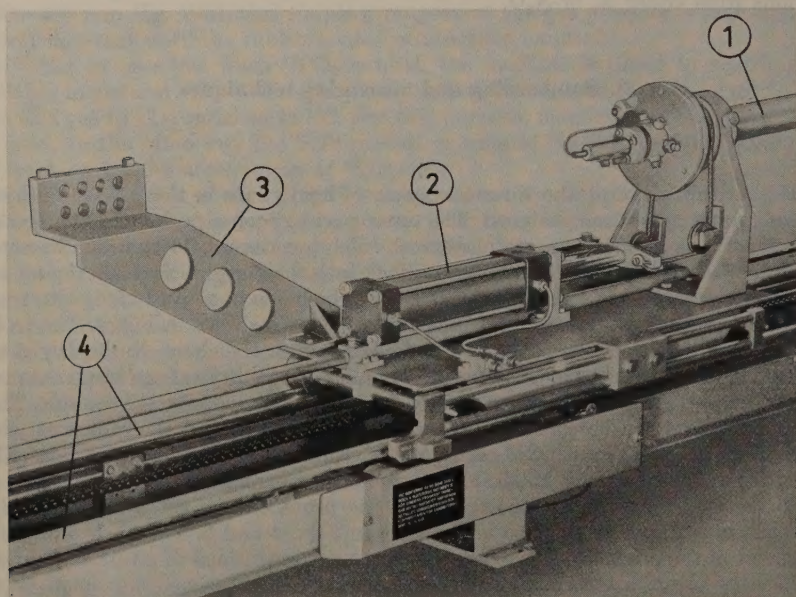


Fig. 5. Photograph of the probe trolley. 1 probe stem. 2 pneumatic cylinder. 3 support for cables and water hoses. 4 tracks.

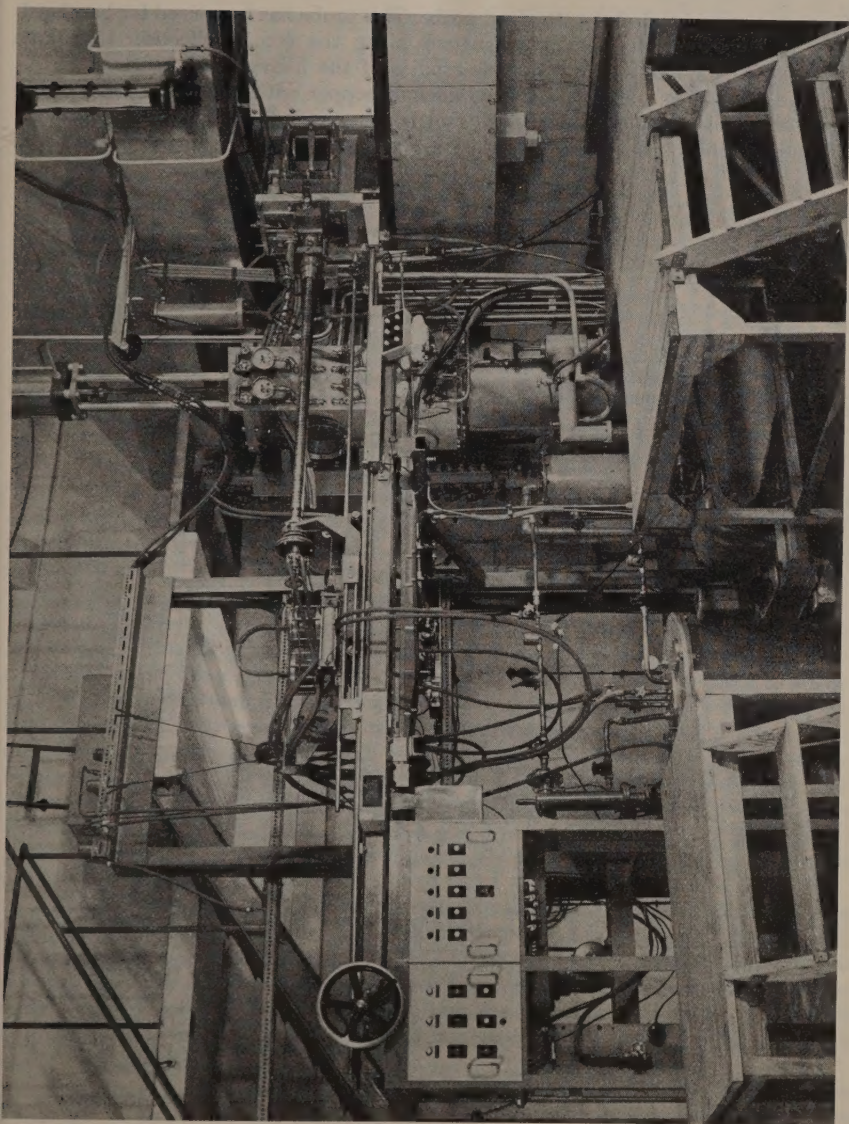


Fig. 6. Arrangement of probe with trolley and tracks (cf. Figs. 4 and 5).

3.2. Standard probe

Fig. 7 shows the head of the standard probe. This probe has been used for bombardments of thick targets, for investigations using the recoil collection technique (compare, e.g., ref. 36) and for various studies of the heavy-ion beams.

The probe head is a water-cooled cylinder of copper with a thin (about 0.6 mm thick) front wall of molybdenum. The two beam openings, which are 180° apart, are defined by means of the holes in the copper clamps attached to the probe head.

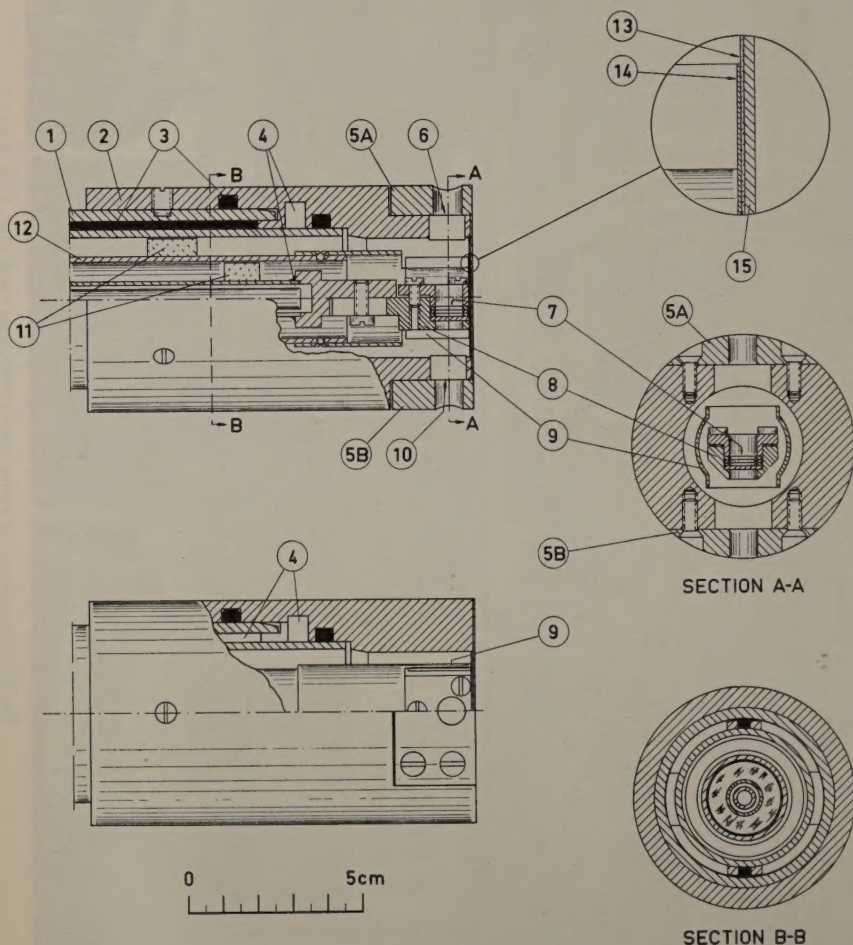


Fig. 7. Drawing of the head of the standard probe. 1 probe stem. 2 probe head cylinder. 3 rubber gaskets. 4 cooling channels. 5 A, 5 B foil clamps. 6 position of bombardment-window foil (aluminium). 7 foil assembly. 8 foil holder. 9 copper shield (part of a Faraday cup). 10 position of measuring-window foil (aluminium). 11 plexi-glass insulators. 12 target holder stem. 13 insulation (Teflon). 14 shield wall. 15 thin end wall (molybdenum).

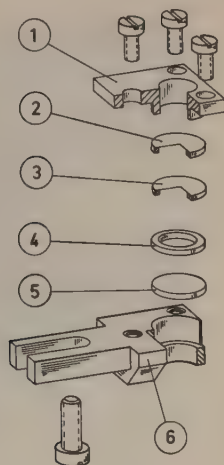


Fig. 8. Exploded view of target holder and foil assembly for recoil experiments (standard probe). 1 clamp. 2 target foil. 3 catcher foil. 4 spacer ring. 5 beam stopper. 6 target holder.

These clamps are also used for attaching foils to the openings. Internally, a water-cooled target holder is fastened to a stem which is insulated from the outer probe stem and can be withdrawn through the surrounding tube. Various types of target holders can be used. Figs. 7 and 8 show the target holder utilized for experiments in which the recoil collection technique is applied.

One of the probe openings is used as a measuring window and is covered with a foil (usually aluminium), the purpose of which is to absorb ions with energies below a specific value. Also, this window prevents low-energy, non-resonant ions from entering the probe when measurements are made. The ion current reaching the target holder is measured by means of a sensitive galvanometer (with a maximum sensitivity of $5 \times 10^{-4} \mu\text{A}$ per scale division). To catch the secondary electrons which are emitted by the surface struck by the beam, the target holder is surrounded by a copper shield arranged as shown in Fig. 7. This shield and the target holder are in electrical contact with each other and together form a Faraday cup. It should be noted that the probe head is in a strong magnetic field which prevents electrons from migrating into or out of this Faraday cup.

The opening opposite to the measuring window is used as the bombardment opening. This is sometimes covered with a foil (usually of aluminium) either for absorbing the low-energy ions which may destroy the internal target by heating, or for degrading the energies of the high-energy ions. The measuring window is always used when the cyclotron is being tuned. After this has been done, the probe is rotated for bombardment. In long-duration bombardments the probe is frequently rotated for check measurements.

A thick target can be bombarded also by clamping it between the foil clamp and the probe head. In this case the target is often provided with a small hole allowing part of the beam to penetrate a measuring window placed behind the target. In this way the beam can be measured continuously during the bombardment.

Withdrawal of the probe from the air lock and detachment of the target holder can be finished within about half a minute after the end of the bombardment.

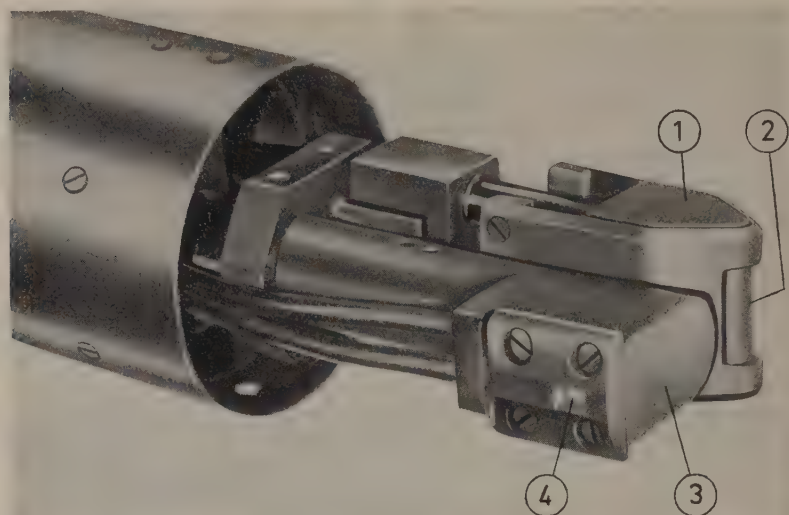


Fig. 9. Inner end of foil probe. 1 foil holder body. 2 foil. 3 measuring arrangement. 4 measuring window.

3.3. Foil probe

The photograph in Fig. 9 shows the inner end of a probe designed for the bombardment of metallic foils which are thick and tight enough to stand direct water-cooling.

The foil is fastened to a plough-shaped holder which in principle resembles one used in the Berkeley 60-inch cyclotron [17]. The arrangement is shown in Fig. 10. The foil holder body has a recess surrounded by a rubber gasket which provides a water-tight seal between foil and holder. Water is sprayed against the back of the foil. The water pressure used is only about $1/4$ of an atmosphere above atmospheric pressure. When bombarding foils of heavy metals (such as platinum and uranium), foil thicknesses of $50\text{--}100\ \mu$ have proved to be suitable to stand this pressure. After the bombardment, the cooling water is quickly removed by blowing with compressed air before the bombarded part of the foil is cut away by means of a scalpel. In this way, and by using the fast withdrawal of the probe, the foil can be detached from the holder within half a minute after the end of the bombardment.

For the adjustment and measurement of the beam, the probe has a separate measuring arrangement (Fig. 11). This is a water-cooled measuring chamber with a beam opening covered with an aluminium foil of suitable thickness. By rotating the probe through 180° , the window is brought to face the beam. The current of ions penetrating the window is collected by a Faraday cup and measured by the beam galvanometer.

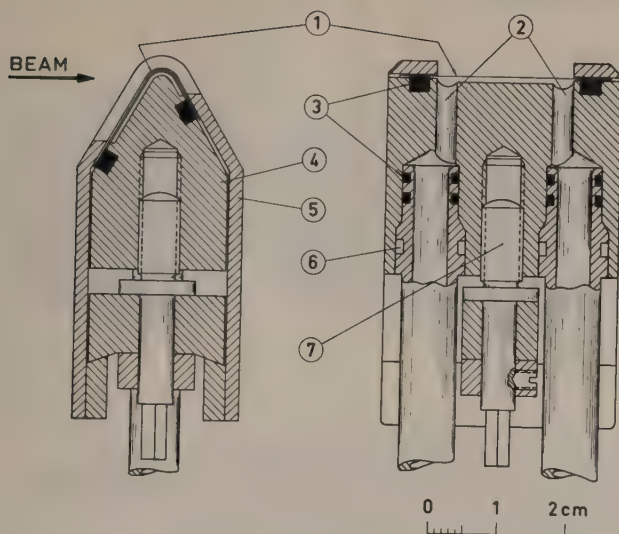


Fig. 10. Foil holder arrangement. 1 foil. 2 cooling channels. 3 rubber gaskets. 4 foil holder body. 5 foil strap. 6 groove for locking screw. 7 strap screw.

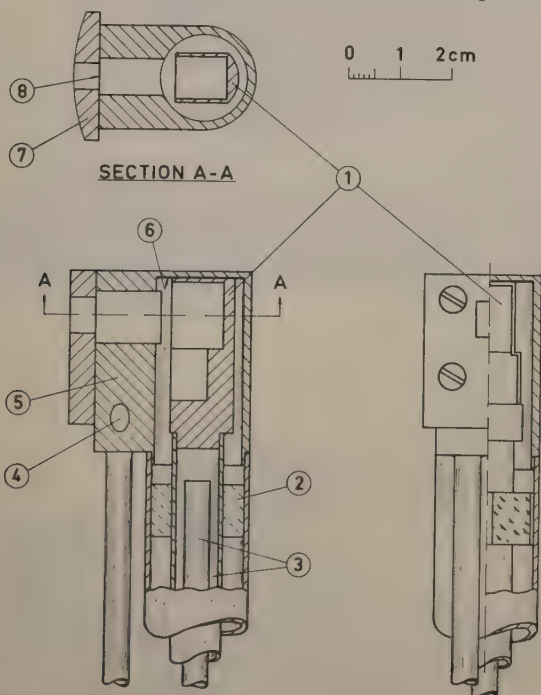
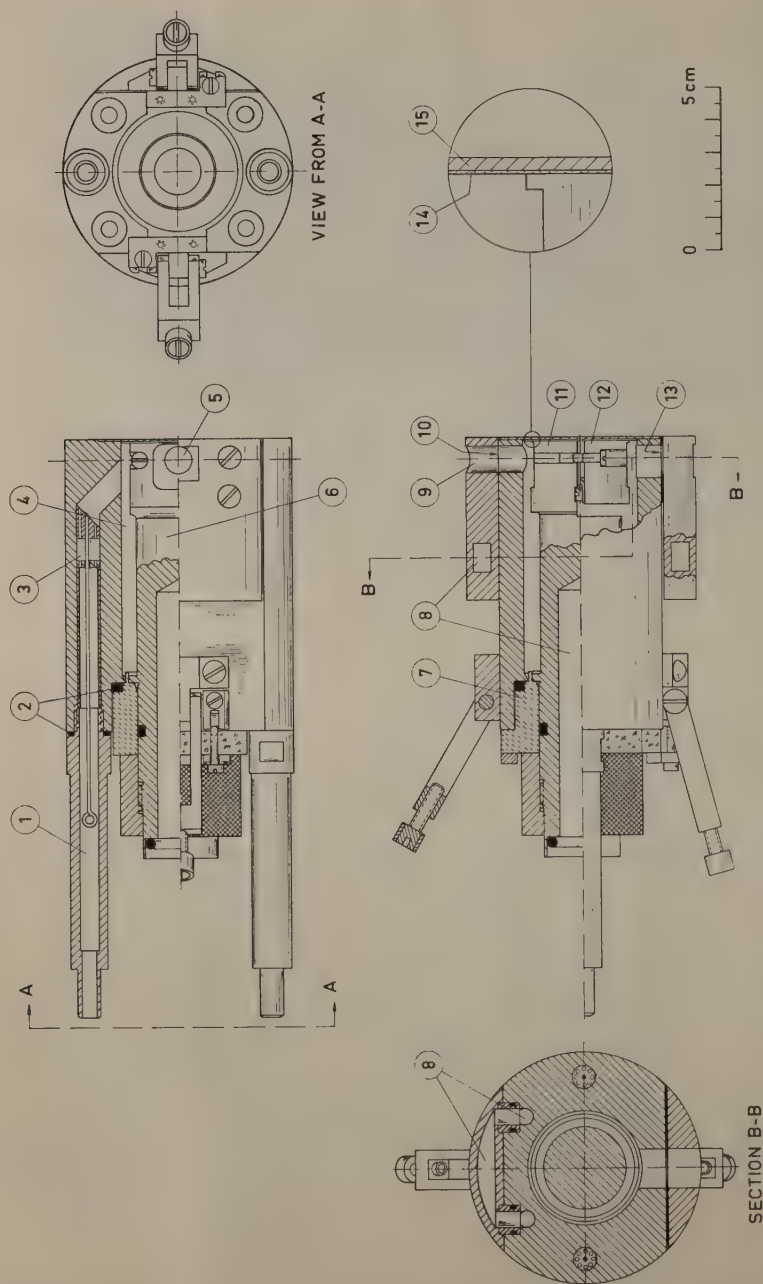


Fig. 11. Measuring arrangement. 1 beam current collector (Faraday cup). 2 plexi-glass insulator. 3, 4 cooling channels. 5 measuring chamber. 6 insulation. 7 foil clamp. 8 measuring window.



SECTION B-B

Fig. 12. The head of the sealed probe. 1. evacuation channel (or cooling-gas channel). 2. rubber gaskets. 3. glass-wool filter. 4. bombardment chamber. 5. measuring opening. 6. target holder. 7. catcher-foil holder. 8. bombardment window foil (aluminum). 9. insulation (Teflon). 10. thin end wall (molybdenum). — The diameter of the bombardment window opening is 8 mm.

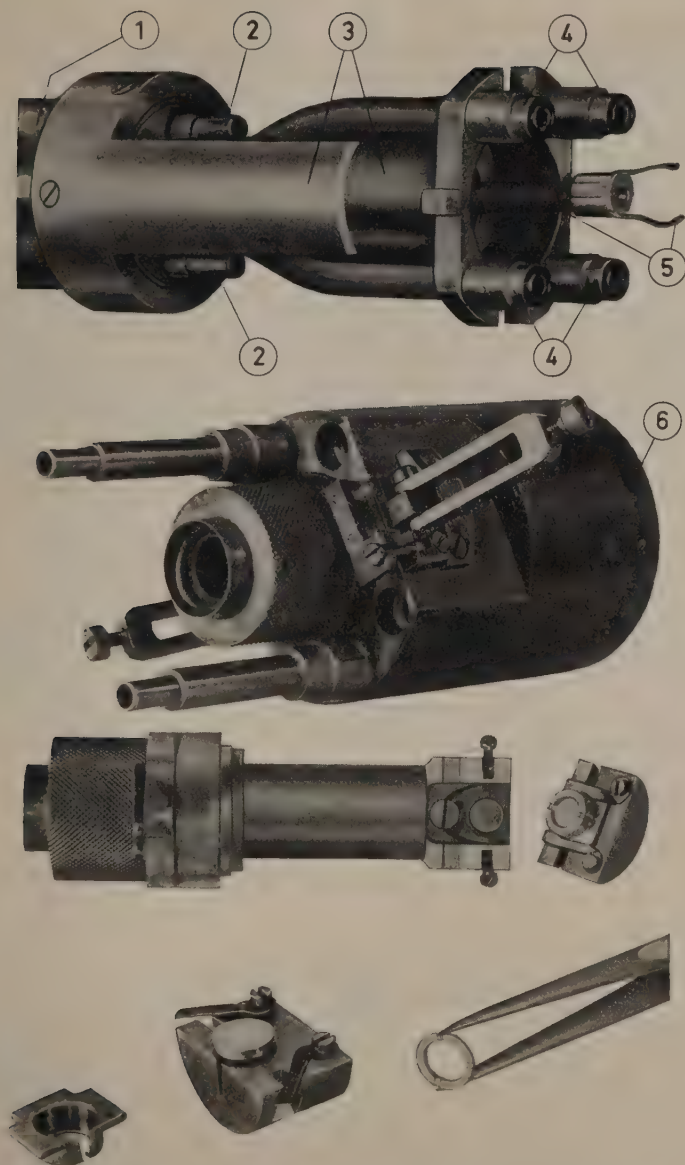


Fig. 13. Photograph showing details of the sealed probe (cf. Fig. 12). 1 probe stem, 2 evacuation pipes (or cooling-gas pipes), 3 probe-head holder, 4 cooling pipes (connections with O-rings), 5 internal cooling pipe with contact fingers, 6 beam window. — The lower part of the figure shows the target holder and the catcher foil assembly.

3.4. Sealed probe

Fig. 12 shows the head of a sealed probe (cf. Fig. 13). This probe was primarily designed for bombardments of curium targets with carbon ions [18].

Among the features of this probe, the following may be mentioned:

1. The bombardment chamber can be used both for thick target bombardments and (as shown in Fig. 12) for experiments using recoil collection technique.
2. The bombardment chamber is sealed off to prevent radioactive dust from migrating into the vacuum system.
3. If necessary, the chamber can be provided with gas cooling.
4. The probe head can be removed from the probe stem in 5–10 seconds. This time includes the time necessary for blowing out the cooling-water channels.
5. The sealed probe head can be quickly dismounted in a glove box. The target- and catcher-foil arrangement, shown in Fig. 14, can be taken apart very easily in such a way that one can remove the catcher foils without touching the target assembly.

With reference to Figs. 12–14, some details of the design will be explained. The outer part of the probe head (constituting the bombardment chamber) is a hollow copper cylinder with a 0.8-mm thick front wall of molybdenum. The two beam openings (the bombardment opening and the measuring opening) are sealed by means of aluminium foils serving as windows. (In the experiments on carbon bombardment

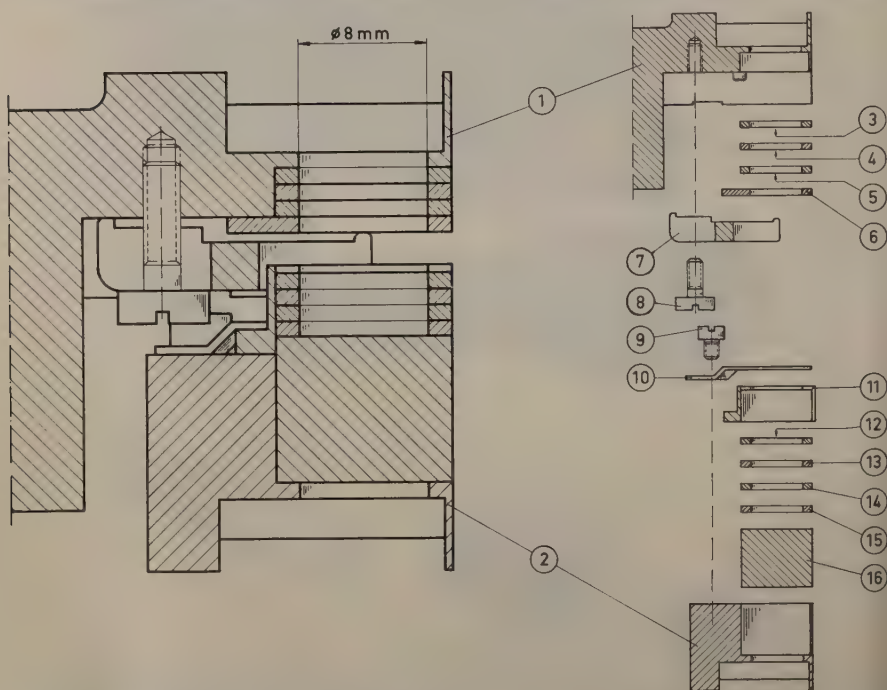


Fig. 14. Target- and catcher-foil arrangement (sealed probe). 1 target holder. 2 catcher-foil holder. 3 cover foil. 4 target foil. 5 cover foil. 6 clamping plate. 7 clamp. 8, 9 clamping screws. 10 clamping spring. 11 clamping hood. 12 catcher foil. 13–15 spacer rings. 16 beam stopper.

of curium [18], the bombardment window was usually $12\ \mu$ thick and the measuring window $118\ \mu$ thick.) The foils are pressed against the foil seats by clamping-blocks of copper. Due to the accurately machined surfaces of the foil seats and the clamping blocks, the joints are sufficiently tight without the use of gaskets.

The copper wall of the probe head has four cooling channels which communicate in pairs via channels in the foil clamping blocks. These blocks are removable, and tightness for the cooling water is achieved by means of O-ring gaskets.

The target-holder shaft is sealed to the outer part of the probe by means of O-ring gaskets. The shaft is hollow for water cooling. Two screws are used for keeping the shaft in position. The probe head is fastened to the probe stem by means of two clamping loops. This arrangement is visible in Figs. 12–13. The cooling channels in the probe-head wall and in the target-holder shaft are automatically connected to the corresponding cooling pipes when the probe head is linked to the probe-head holder. These joints are also tightened by O-ring gaskets. The water line connected with the target-holder shaft consists of two concentric pipes. The inner one of these carries two contact fingers which provide contact between the target holder and the galvanometer lead (connected to the rear end of the water line concerned).

The interior of the probe head (bombardment chamber) is evacuated via two channels (visible in Fig. 12). These are provided with glass-wool filters which prevent dust from moving into the vacuum system. If necessary, cooling gas, e.g. helium, can be pumped through the bombardment chamber at a low pressure. This is done via the evacuation channels, which, for this purpose, have to be connected with the cooling-gas pipes in the probe stem.

The target- and catcher-foil arrangement as used in the carbon bombardments of curium [18] is shown in Fig. 14. The target foil (curium on aluminium backing [18]) was enclosed within two cover foils which had the purpose of preventing radioactive dust from entering the space outside the target holder. The foil facing the beam window was a $10\text{-}\mu$ thick aluminium foil. The cover foil between the target and the catcher foil had to be very thin in order not to stop the recoiling products of interest (cf. ref. 19). In the actual case [18] a $50\text{--}100\ \mu\text{g}/\text{cm}^2$ aluminium foil was used. This foil was prepared by an evaporation procedure described previously [19]. A thick Tygon film ($1\ \text{mg}/\text{cm}^2$) was usually used as catcher foil.

All foils were mounted to 1-mm thick aluminium rings with inner and outer diameters of 8 and 11 mm, respectively.

3.5. Foil-changer probe

As will be described in more detail in Section 5, the energy distributions of the internal beams of, in particular, $^{12}\text{C}^{4+}$ ions have been preliminarily studied by means of the method based upon measurements of the absorption of ions in metallic foils of known thicknesses. For this purpose the currents of ions penetrating various thicknesses of aluminium have been measured. Due to the fact that the exact charge state of the penetrating ions is not known, it is obvious that only approximate distribution curves can be obtained in this way. However, the method has the advantage of giving immediate information in cases where the highest degree of accuracy is not necessary. To make possible such investigations of range distributions in metallic foils, a foil-changer probe has been designed.

A drawing of the probe head is shown in Fig. 15. Inside the probe head are four foil holders which can be pushed into the beam or pulled back again by means of a

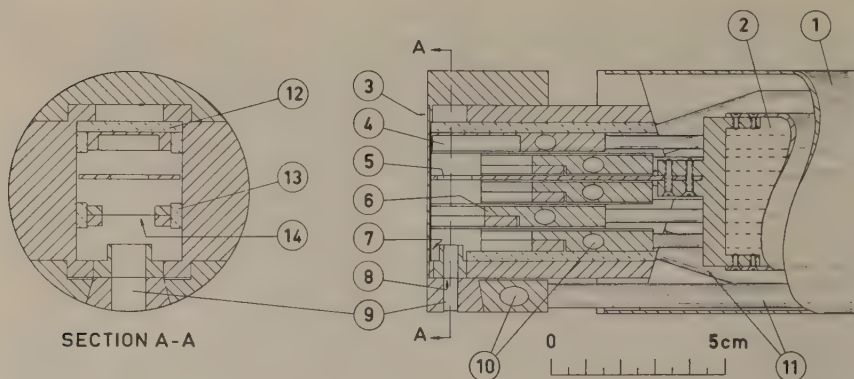


Fig. 15. Foil-changer probe. 1 probe stem. 2 plexi-glass insulator. 3 thin end wall (molybdenum). 4 current collector. 5 beam defining opening. 6 one of the foil holders. 7 Teflon insulation. 8 position of beam-window foil. 9 beam entrance. 10 cooling channels. 11 cooling pipes. 12 plexi-glass insulation. 13 Teflon insulation. 14 foil.

magnetic device at the rear end of the probe. This arrangement is schematically shown in Fig. 16. When the plunger is attracted by the magnet, the foil holder coupled to this plunger is moved inwards. The outward motion is achieved by the spring load (in addition to the atmospheric pressure on the lead-through bellows). A shallow Faraday cup is used for measuring the beam, which enters the probe head through the entrance slot. A thin aluminium window (about 10μ thick) in this slot prevents ions of very low energies from entering the probe.

The internal foil holders are insulated from the outer probe and from each other. In this way the currents absorbed in the foils can be measured if desired. The investig-

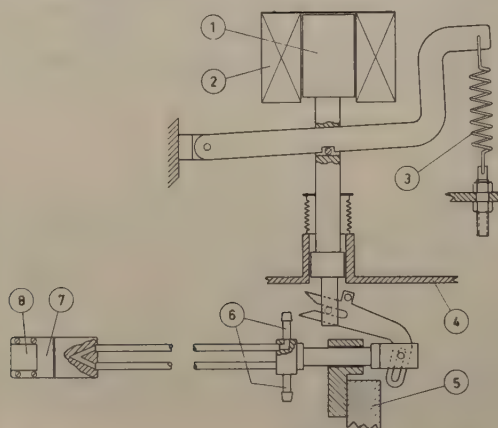


Fig. 16. Schematic drawing of the foil-changer arrangement. 1 plunger. 2 solenoid. 3 spring. 4 vacuum envelope. 5 insulator. 6 cooling-air connections. 7 foil clamp. 8 foil.

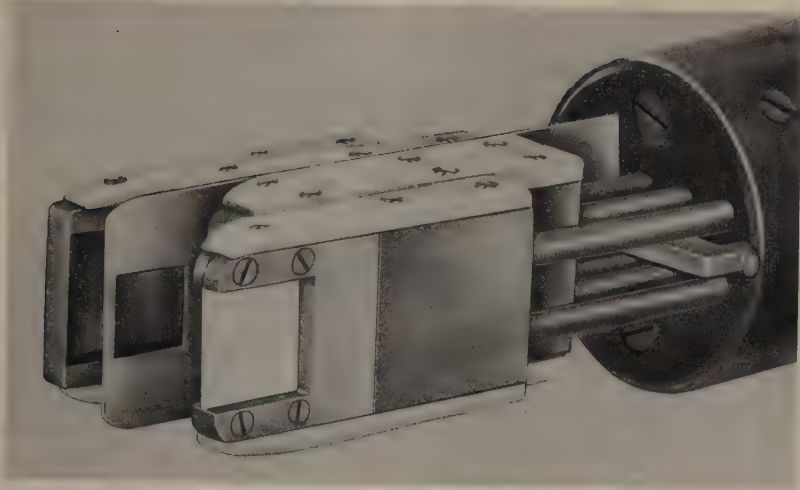


Fig. 17. Photograph showing the foil holders, the plate with the beam defining opening and the current collector (in the background).

ations described in Section 5 have been performed by measuring the beam currents reaching the current collector after penetration of one or several foils. By combining the four movable foils and the window foil in various ways, a variety of absorber thicknesses can be obtained. Fig. 17 is a photograph of the foil holders and the current collector.

The opening in the copper plate placed between two of the foil holders (Figs. 15 and 17) has the purpose of defining the beam reaching the current collector. It has such dimensions that ions coming from the entrance slot in approximately straight trajectories can reach the bottom but not the edges of the current collector. The arrangement with foils on both sides of this beam-defining opening has been chosen for mechanical reasons. The edge effect, which might be expected due to the position of the foils with respect to the entrance slot and the beam-defining opening, has been studied in several runs and found negligible.

3.6. A camera arrangement

If the ranges of heavy ions in nuclear emulsions are known, such emulsions can be used to give accurate information on the energy distribution of the ions. Different ways of applying this method to the study of internal cyclotron beams of heavy ions have been reported.¹ In some experiments the beam currents have been greatly reduced by reducing the dee voltage or the ion-source arc current [20], in others the beams have been investigated under normal bombardment conditions by exposing the emulsions to ions which have been elastically scattered [21]. In the first-mentioned case it has been necessary to take into account the possibility that the energy distribution may be changed due to the changes in the cyclotron conditions [20].

¹ At the Nobel Institute of Physics Professor H. Slätis has used photographic emulsions in investigations of the energy distribution of internal beams of deuterons accelerated in the 80-cm cyclotron (to be published).

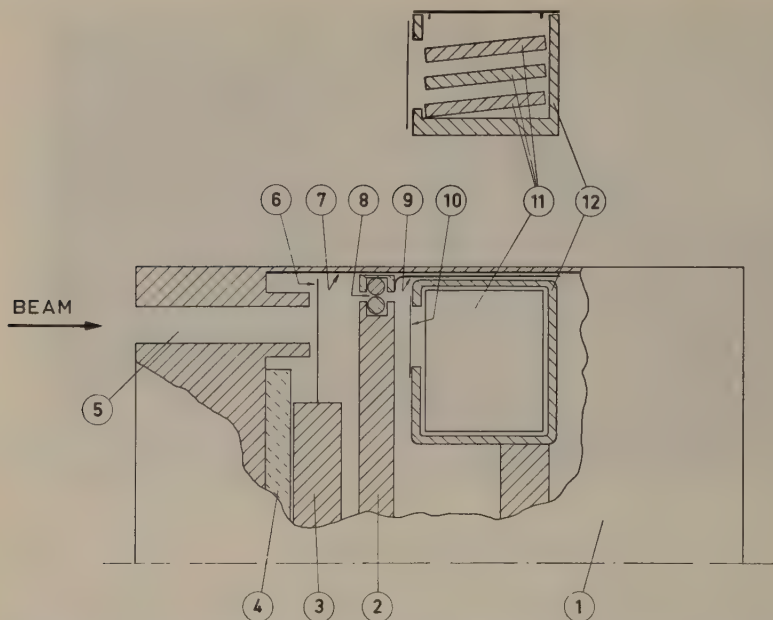


Fig. 18. Schematic representation of the camera arrangement. 1 probe head. 2 shutter. 3 foil holder. 4 insulation. 5 beam entrance. 6 measuring foil. 7 insulation. 8 shutter slot. 9 flexible copper curtain. 10 beam-window foil. 11 photographic plates. 12 plate holder.

In a few preliminary attempts to study the internal ^{12}C beams of nuclear emulsions under normal (or almost normal) bombardment conditions, the present author arranged the foil-changer probe as a camera. As the experiments were done very hastily a few days before the cyclotron had to be shut down for remodeling, there was no time to modify the camera arrangement as was found necessary in the course of the experiments. However, already in its preliminary performance the arrangement gave some useful results (see Section 5).

Fig. 18 is a schematic representation of the photographic device. A plate holder with three plates (Ilford C-2) was attached to one of the foil holders. The plates were tilted at about 8° to the horizontal plane. The plate holder was provided with a beam opening covered with a thin metallic foil (aluminium or nickel). In front of this was a shutter having a narrow slot, the width of which could be adjusted from a few microns upwards. The shutter was also attached to a foil holder (the second one from the entrance slot). Before the exposure was started, the shutter was pushed towards the probe-head front wall by means of the magnetic device described above (Fig. 16). In this position the shutter slot did not expose the foil-holder window to the beam. In order to expose the emulsions, the shutter was made to pass the beam window by switching off the current in the solenoid. The spring caused the shutter to move with very high velocity. As the shutter moved across the foil-holder window, the flexible copper curtain forming part of the shutter was withdrawn from a narrow pocket between the foil holder and the front wall of the probe and covered the beam window.

To adjust the beam, an aluminium foil attached to the foil holder next to the entrance slot was pushed into the inner position, and the beam penetrating the foil and hitting the shutter was measured. For this purpose the shutter had been provided with overhangs above and below to catch secondary electrons. Before exposing the emulsions, the measuring foil was pulled back. In the investigation reported in Section 5 the measuring foil had a thickness of about 28 mg/cm².

4. Range-energy relations

In the work on heavy ions concerned in this paper the energies of the ions were almost exclusively determined from their ranges in metallic foils. For this purpose, calculated range-energy curves were used as no experimental data were available (except for ranges in nickel for nitrogen ions with energies below 30 MeV [22]). In the Stockholm experiments aluminium foils were used.

As regards range-energy relations for photographic emulsions some data were known for carbon ions from Miller [23], for nitrogen ions with energies below 30 MeV from Reynolds and Zucker [24] and for nitrogen ions from Chaminade *et al.* [25]. Recently range-energy relations have been published by Parfanovich *et al.* [26] for nitrogen and oxygen ions in photographic emulsions.

Calculations of ranges for heavy ions meet with difficulties, as for this purpose knowledge of the relation between the effective charges of the ions and their velocities (see, e.g., [27]) is imperative. This is illustrated by the fact that, for instance, ions such as those of nitrogen and oxygen must have high energies to be completely stripped. According to recent estimates by Parfanovich *et al.* [26], the ions mentioned reach their maximum charge in the range 70–90 MeV and 100–120 MeV, respectively.

Calculations of ranges for heavy ions have been carried out by several authors, amongst them Papineau who has calculated range-energy curves for various heavy ions (from Li to Ne ions) in Ilford C-2 emulsions [28].

Papineau's calculations were based upon a semi-empirical curve giving Z_{eff}/Z as a function of $v/Z^{1/2}$ (Z_{eff} and v being the effective charge and velocity, respectively, of an ion of atomic number Z). Up to a value for $v/Z^{1/2}$ of about 5×10^8 cm/sec (corresponding to a Z_{eff}/Z value of about 0.9), Papineau based the curve on available experimental data (for references see [28]). After the point mentioned the curve was continued by extrapolation. Recently Papineau modified this extrapolated part of the curve [29]. According to this modified curve, Z_{eff} reaches its maximum at a $v/Z^{1/2}$ value of about 9×10^8 cm/sec (the corresponding value taken from the curve in ref. [28] being about 15×10^8 cm/sec).

The energies for C, N and O ions given in this paper (in Table 1 and in Section 5) have been determined from range-energy curves calculated by Papineau [29] on the basis of the above-mentioned modified curve for Z_{eff}/Z . In all cases range data for aluminium were used¹. Neon ion energies have been determined from ranges in aluminium according to a range-energy relation calculated by the author (using Papineau's modified effective-charge curve).

¹ As the present paper was going to press the author's attention was drawn to a recent experimental determination of range-energy curves for carbon, nitrogen and oxygen ions in aluminium (U. Z. Oganessian, J. Exptl. Theoret. Phys. U.S.S.R., 36, 936 (1959), in Russian). The agreement between these curves and those calculated by Papineau [29] is very good.

5. Energy distributions of heavy ions

5.1. General

As already mentioned, the energy distribution of six-charged heavy ions produced in a two-step process (i.e., by pre-acceleration of doubly-charged ions) is continuous. The distribution maximum is far below the nominal energy (compare, e.g., [8]). This may be illustrated, for instance, by the energy distribution of $^{20}\text{Ne}^{6+}$ ions in the 225-cm cyclotron. According to foil absorption measurements at a radius of 80 cm, where the nominal ^{20}Ne ion energy is about 170 MeV, roughly half the intensity of all neon ions with energies above 100 MeV was due to particles having energies in the range 100–120 MeV.

When $^{12}\text{C}^{4+}$ ions were first accelerated in the 225-cm cyclotron it was, of course, expected that in this way a carbon beam with a narrow high-energy peak would be produced. Foil absorption measurements performed at an early stage indicated, however, that this was not the case, although the energy spread was less than that of the six-charged carbon ions. Indications of a broad peak were also found by analyzing experiments on ranges of astatine atoms produced by ^{12}C ions [19].

Further investigations by means of foils showed that, together with the broad high-energy peak, there was also a low-energy component.

As will be described in the following, later experiments have shown that under certain conditions it is possible to obtain (with the ion source described in this paper) a relatively narrow and well-defined high-energy peak.

5.2. Some investigations of the energy distribution of $^{12}\text{C}^{4+}$ ions

From the experience gained from the acceleration of six-charged heavy ions by the above-mentioned two-step process, it is known that the spectrum of the ions is affected by cyclotron conditions, for instance the gas pressure (cf. [8]).

In the 225-cm cyclotron the foil-changer probe has been used for a series of investigations of the energy distribution of ^{12}C ions under various cyclotron operating conditions, in particular under various ion source conditions. As already mentioned, this method can give only approximate distribution curves due to the fact that the average charge of ions leaving a degrading foil with various velocities is unknown. For this reason the current measured does not give an exact measure of the number of ions. However, the foil absorption method was considered to be accurate enough for the present study as this concerned relatively great changes in the energy distribution. As mentioned previously, the advantage of the method is that it can give immediate information.

Unfortunately, the experiments using the foil-changer probe were carried out at a time when the ion source did not work reliably due to arcing at the filament clamps. Therefore, the ion source had to be run at a maximum of 300 volts in order to keep the operation of the source stable during the period necessary for the measurement of an energy spectrum (at least 5–10 minutes). Due to this, it was not possible to measure energy spectra under the conditions used in the best carbon bombardments, as in these runs arc voltages of about 350–400 volts were utilized.

Among the range-distributions obtained by means of the foil-changer probe, a few will be discussed in the following. Preliminary results of an investigation using photographic emulsions will also be shown. All measurements presented here were

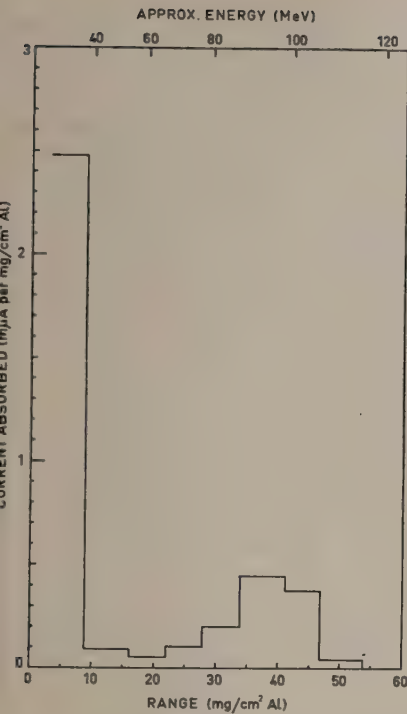


Fig. 19.

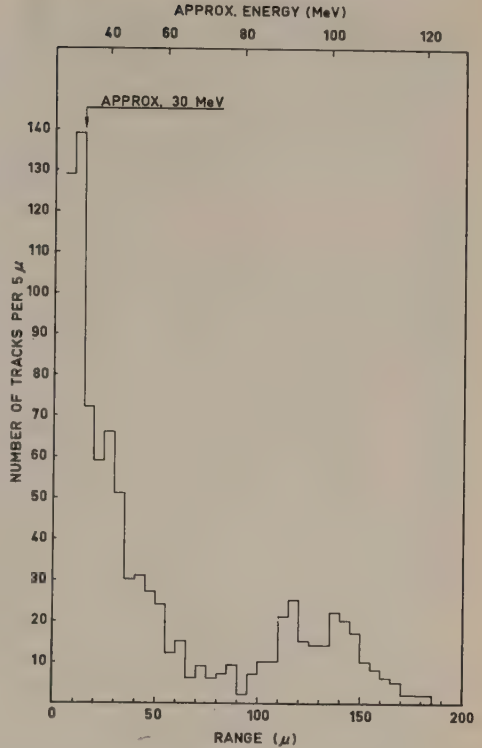


Fig. 20.

Fig. 19. Range distribution of ^{12}C ions in aluminium (for ranges above $3 \text{ mg/cm}^2 \text{ Al}$). Arc data: 200 volts and 2 amperes. The ion source was displaced towards the east dee as shown in Fig. 2. The energy scale is based on a range-energy curve calculated by Papineau [29].

Fig. 20. Range distribution of ^{12}C ions from a preliminary investigation using Ilford C-2 emulsions (100μ thick). The energy scale is based on curves calculated by Papineau [29]. Correction has been made for the degrading of the energies in the $10\text{-}\mu$ aluminium foil covering the plate holder opening. Arc data: 200 volts and 2 amperes. The position of the ion source was about the same as when measuring the spectrum in Fig. 19.

performed at a radius of 80 cm. In all cases only ions with energies above about 15 MeV were measured due to the absorption in the beam window ($10\text{-}\mu \text{ Al}$).

Fig. 19 is a distribution histogram obtained with the ion source displaced from the centre of the dee gap (about the position indicated in Fig. 2). In this run the arc voltage and arc current were relatively low, 200 volts and 2 amperes, respectively. The dee-to-dee voltage was about 200 kV (peak value). The energy distribution is characterized by a relatively intense low-energy component and a rather broad high-energy component.

Fig. 20 shows a distribution histogram obtained from a preliminary investigation using photographic emulsions (Ilford C-2, 100μ thick). In this case the arc data and

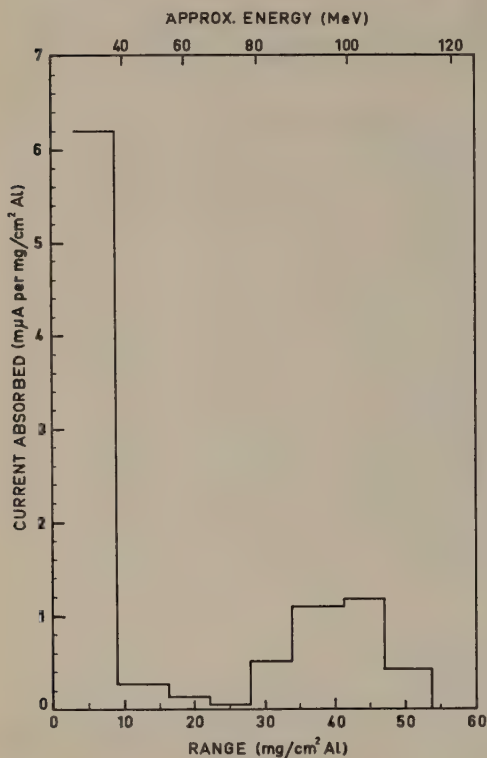


Fig. 21.

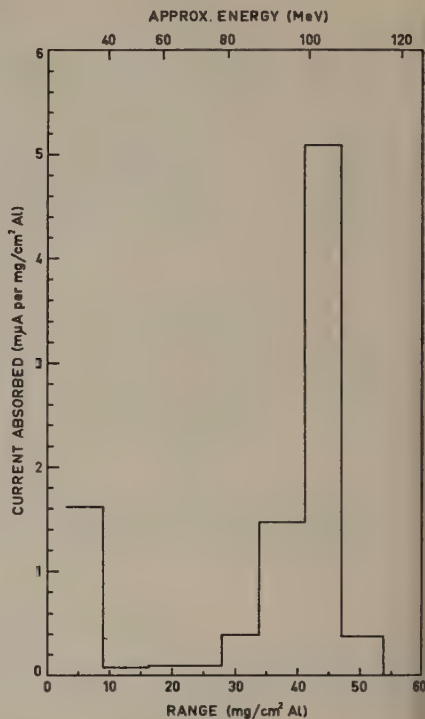


Fig. 22.

Fig. 21. Range distribution of ^{12}C ions in aluminium (for ranges above $3 \text{ mg/cm}^2 \text{ Al}$). Arc data: 300 volts and 2 amperes. The position of the ion source was about the same as when measuring the spectra in Figs. 19 and 20.

Fig. 22. Range distribution of ^{12}C ions in aluminium (for ranges above $3 \text{ mg/cm}^2 \text{ Al}$). Arc data: 300 volts and 2 amperes. The ion source was placed near the centre of the dee gap.

the dee voltage were the same as in the above-mentioned run. Only tracks longer than 5μ were measured. The distribution was obtained by investigating two of the three plates exposed (the arrangement being in accordance with Fig. 18). With the shutter slot used (55μ) the track density was too high within a narrow region hit by the most intense part of the beam. The tracks measured (in total about 900) were all in the vicinity of this region. In its general trend the distribution obtained in this way is apparently rather similar to that in Fig. 19. However, the preliminary nature of the results presented in Fig. 20 must be emphasized. The energy determination using Papineau's range-energy curve indicates that the maximum of the low-energy peak is below about 30 MeV.

Fig. 21 shows a distribution histogram obtained with the foil-changer probe under similar conditions except for the arc voltage which was 300 volts in this case. The intensities of both peaks of the spectrum were now increased, but the general shape of the high-energy component seemed to be about the same.

Quite a different energy distribution was observed in runs in which the ion source was positioned near the centre of the dee gap. The result of an investigation under such conditions is shown in Fig. 22. The arc data and the dee voltage were the same as in the run represented by Fig. 21. The ratio between the intensities of the two peaks was now markedly changed and so was the shape of the high-energy component. According to the histogram, there is a narrow high-energy peak with the maximum very near to the nominal energy corresponding to the radius used (about 103 MeV).

The results obtained show clearly that the energy distribution is very sensitive to changes in the lateral position of the ion source.

Effat and Fremlin [30] have given a plausible explanation for the relative broadness of the C^{4+} spectrum obtained under certain conditions, as well as for the appearance of the low-energy peak. This explanation is based on considerations of second-harmonic acceleration. Effat and Fremlin show that second-harmonic acceleration is possible for ions which need two radio-frequency cycles for one revolution, provided the centre of revolution is to one side of the dee gap. If the cyclotron is adjusted to resonance for $^{12}C^{4+}$ ions, second-harmonic acceleration will be possible for $^{12}C^{2+}$ ions under the above-mentioned condition. In this case the doubly-charged carbon ions must move in such orbits that they can spend $1/2$ radio-frequency cycle between successive crossings of the dee gap on one side of this gap and $1\ 1/2$ radio-frequency cycles between the crossings on the other side. The acceleration process under these conditions is complicated [30] by the fact that the eccentric orbits precess due to the radially decreasing magnetic field. In a similar way as $^{12}C^{2+}$ ions may be accelerated in a second-harmonic process, $^{12}C^{1+}$ ions may be accelerated in a fourth-harmonic process [30]. According to Effat and Fremlin the broadening of the $^{12}C^{4+}$ peak is most likely due to fourth- or second-harmonic acceleration of singly- and doubly-charged ions. On the same basis these authors explain the low-energy peak as representing $^{12}C^{2+}$ ions.

As already mentioned, the number-range histogram given in Fig. 20 indicates that the low-energy peak is below 30 MeV. For a doubly-charged carbon ion moving in an orbit with the centre coinciding with the geometric centre of the magnet the energy at the radius concerned would be about 26 MeV. For geometrical reasons, the C^{2+} energy can, under no circumstances, exceed about 30 MeV at this radius. Considering the energy distribution shown in Fig. 20 it seems very likely that the low-energy part of this distribution (the region below about 60 MeV) contains both a narrow component of C^{2+} ions in accordance with the explanation given by Effat and Fremlin [30] as well as C^{4+} ions produced by stripping of singly- or doubly-charged ions.

If the tank pressure is raised by letting argon into the vacuum system the current of carbon ions (produced under conditions of resonance for C^{4+}) is increased. Foil absorption measurements have shown that this intensity increase occurs both for the high-energy component as well as for the measured part of the low-energy component (i.e., that part of the low-energy component which contains ions with energies above about 15 MeV). This increase of the beam intensities for both components must be caused by stripping processes (most likely due to fourth- or second-harmonic acceleration).

6. Applications

When the acceleration of heavy ions in the Stockholm 225-cm cyclotron was first tried (in 1953), no nuclides of atomic numbers higher than 98 had been reported. The first production of a transuranium element by means of high-energy heavy ions had been performed at Berkeley [31] in 1951. For these experiments carbon ions accelerated in the Crocker 60-inch cyclotron were used. In the spring of 1953 a group¹ at the Nobel Institute of Physics started experiments with the goal of studying transuranic nuclides produced by the heavy-ion beams available in the 225-cm cyclotron. It was considered quite possible to produce in this cyclotron useful beam currents of nitrogen and oxygen ions with energies above the potential barrier for reactions with uranium. Therefore, the group mentioned decided to use these ions in attempts to produce transcalifornium elements. In a series of experiments uranium was bombarded with $^{14}\text{N}^{6+}$ ions for the purpose of looking for an isotope of element 99. At the time of this work, however, the essential experimental conditions were of a rather preliminary nature, and no positive results were obtained. From the autumn of 1953, conditions were successively improved. From this time up to March 1958, when the cyclotron was shut down for remodeling, the internal heavy-ion beams produced in this machine were used by various groups, in particular for experiments in the transcalifornium field [32, 18, 33] and for investigations of alpha-active neutron-deficient nuclides in the polonium region [34–38]. In other experiments heavy ions were used to study reactions with cobalt and copper [39, 40]. In a series of investigations using ^{12}C ions, nuclear stopping of astatine atoms was studied [19]. Using the neon beam fission yield studies have been undertaken [41].

In addition to the experiments in the transcalifornium range reported above (or in refs. given above) mention should be made of a series of attempts to produce element 102 by means of neon ions. As soon as beams of ^{20}Ne and ^{22}Ne ions became available in the 225-cm cyclotron (April 1955) these beams were used to bombard uranium foils in order to investigate if alpha-active products which could possibly be ascribed to an isotope of element 102 were formed². In order to provide as effective cooling of the uranium foil as possible during the bombardment (to avoid evaporation of the reaction products of interest) the foil probe described in this paper was designed. Many experiments were performed, but no indication of an activity which could be ascribed to element 102 was found in any of them. Among possible reasons for this, the predominance of the fission process, as discussed by Thompson [42], may be mentioned.

Finally, a preliminary result of another investigation using neon ions may be mentioned. Some years ago (mainly in 1956) neutron-deficient product nuclei from bombardments of gold by neon ions were studied. In these experiments it was found [43], for instance, that two short-lived alpha-activities, which had not previously been reported, appeared in the purified astatine fraction. One of them had a half-life close to 3 minutes and an alpha-particle energy of roughly 6.3 MeV. The other one was found to have a half-life of about 12 minutes and an alpha-particle energy of approximately 6.0 MeV.

¹ The members of this group were: Professor J. O. Rasmussen, Jr., of the Radiation Laboratory, Berkeley, (part of 1953), Drs. W. Forsling, L. W. Holm, L. Melander, B. Åström and the present author.

² This investigation was made by Dr. S. G. Thompson of the Radiation Laboratory, Berkeley, (part of 1955), Drs. W. Forsling, L. W. Holm, L. Melander, B. Åström and the present author.

At this time it could not be entirely excluded that these activities could be due to decaying daughter products of polonium formed from astatine isotopes by electron capture. A thorough investigation of the alpha-decay properties of light polonium isotopes [34-37] showed, however, that the activities in question had to be ascribed to astatine. According to information obtained late in 1958, these astatine alpha disintegrations had independently been found by Asaro and co-workers [44]. It has not yet been possible in the Stockholm experiments to make definite mass assignments. The investigation will be reported in detail later [43].

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